

December 4, 1978 M. Harrison

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MA

MAGNET APERTURE AND EXTRACTIONSummary

In this design status report we shall show the need to keep the maximum amplitude orbit oscillations in the Tevatron to within ± 2.0 cms horizontally, with the vertical orbit controlled to within ± 3 mms. Under this aperture limitation, we shall show extraction losses and beam spot size instabilities are unacceptably high. We shall then discuss a modification to the lattice across the long straight sections which provides considerable improvements over the normal lattice. Only slow resonant extraction ($1/3$ and $1/2$ integer) will be considered.

Aperture

An accurate estimate of the effective magnet aperture is essential when considering the extraction process in detail, since it is extraction (and possibly injection) which will explore this aperture to its fullest extent. After deriving an effective machine aperture one can then start to make realistic calculations on such topics as horizontal or vertical extraction, orbit stability, and the effect of the aperture on the overall design of the extraction system.

In calculating an effective aperture we have used the design fields for the magnets rather than the measured fields on the limited sample of available dipoles. The validity of this approach rests on the assumption that the correction coil package will be able, in some as yet unspecified fashion, to successfully apply the required adjustment to the lower three harmonic components (quadrupole, sextupole, octupole) of the superconducting dipoles. This cancellation of lower order terms in the harmonic field analysis would result in magnetic fields very close to the design fields. Figure 1 shows a field plot of B_y versus x for dipole 115 (picked at random but representative of the early series

of dipoles). The solid line gives the measured field, the dotted line the design field. Figure 2 shows the same magnet with the lower harmonics suppressed, the resultant field is now similar to the design values.

The method used to determine the effective aperture in a machine comprising of dipoles of this type is relatively straight forward. We perform a computer simulation of an extracted beam (a brief description of the program is given in the Doubler Design Report, October 1978) and wait and see where the orbits start to behave erratically. There is nothing special about an extraction orbit, similar results would be obtained from any large amplitude orbit. The advantage to this technique lies in the fact that we know the expected behavior of the extraction separatrices. Figure 3 shows a phase space plot of a $1/2$ integer extraction separatrix calculated for perfect dipoles with an infinitely large aperture. Figure 4 is an identical calculation performed with design dipoles. The arrow indicates the position where the orbit starts to diverge significantly from the ideal fields. This position corresponds to a maximum amplitude in the machine of ~ 3.15 cms. Figures 5 and 6 show the behavior for momentum shifts of $\frac{\Delta p}{p} = \pm 0.05\%$. It is immediately apparent that orbits begin to behave pathologically at much smaller amplitudes than that of Fig. 4. The reason for this is that without any off-momentum component to the beam in the first approximation an orbit is symmetric about the closed orbit, and as such tune shifts induced by the higher order field harmonics will tend to cancel. An off-momentum orbit ($\sim \pm 1.5$ mms for $\frac{\Delta p}{p} = \pm 0.05\%$) which will destroy this first order cancellation and hence produce appreciable tune shifts (seen as rotations in the phase space plots) for much smaller amplitude oscillations. The results of these calculations put a maximum horizontal effective aperture of $\sim \pm 2.0$ cms.

The effective vertical aperture can be calculated in a similar fashion to that of the horizontal aperture. The end result, however, can be seen by comparing horizontal and vertical fields versus vertical offset as shown in Figs. 7 and 8 with that given in Fig. 2. The effective vertical aperture is ~ 3 mm smaller than the effective horizontal aperture.

The reduction in horizontal aperture due to vertical beam displacements is demonstrated in Figs. 9 and 10, showing the same fields as in Fig. 2 but with vertical offsets of 0.1" and 0.2". A vertical offset of 0.2" shows a marked decrease in horizontal aperture, which indicates a need to control a vertical orbit to within ± 3 mms to avoid limiting this aperture.

To summarize the results of this section we can say that the effective horizontal aperture of the Tevatron for large amplitude orbits is ± 2.0 cms, which is some 3-5 mms larger than the vertical aperture. Because of the relative aperture sizes horizontal extraction is favored over vertical. The beam must be controlled vertically to within ± 3 mms to avoid limiting the existing horizontal aperture.

Extraction

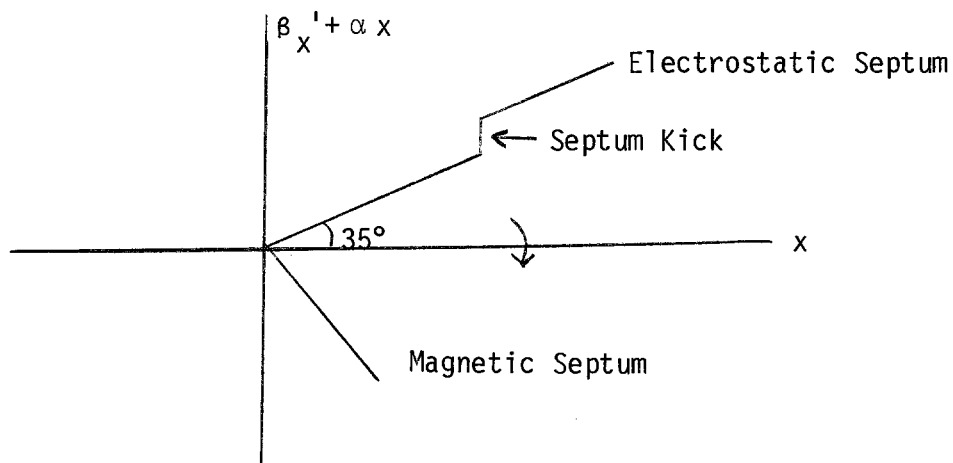
In this section of the design status report we shall examine the behavior of the extraction process with respect to the aperture limitations derived in the previous section.

The superconducting design of the Tevatron requires the "warm" elements of the extraction system (the magnetic and electrostatic septa) to be placed in the long straight section. Recent studies on beam induced dipole quenches (Cox et al, TM-828-A) demonstrate the need to shield the superconducting magnets from the beam losses at the septa. This would imply positioning the septa at the

upstream end of the long straight section. Optimization of the extraction efficiency and the strength of the septa indicate the need to have these elements positioned in a high beta section of the lattice. The horizontal beta value across a long straight section grows from 50 ms at the upstream end to 100 ms at the downstream end, which would suggest the need to position the septa at the downstream end of the long straight section. The compromise position for the septa that we have chosen is in the middle of adjacent long straight sections with a beta value of 70 ms.

The nonlinear fields used for slow resonant extraction (quadrupole, sextupole, and octupole) will be provided by the superconducting correction coils which are distributed uniformly around the machine, allowing us the liberty of choosing any phase angle for the separatrix at the septa, without having to worry about whether suitable locations can be found in the lattice for extraction magnets. This use of the correction coils for extraction purposes (as well as correction elements) is permissible providing that we do not require greater fields than they can produce. Nowhere in this report are we using more than 50% of the field strength of the correction coils as currently envisaged.

The relative phase advance between two septa at identical places in adjacent long straight sections is $\sim 75^\circ$. Maximizing extraction efficiency while maintaining a 2.0 cm aperture and adequate separation between the extracted and circulating beam requires a phase angle of $\sim 35^\circ$ at the electrostatic septum as shown below:



A phase angle greater than 35° would start to seriously increase the extraction losses which are proportional to $1/\cos\theta$ (for everything else fixed) while a smaller phase angle would drive the separated beam at the magnetic septum uncomfortably close to the circulating beam. During the extraction process as the stable phase space region shrinks towards zero the separatrices undergo shifts in position which smear the phase space. To take account of this fact we make calculations for the two extremes: zero stable phase space, and $.04\pi$ mm mrad stable phase space (the current main ring value).

Figures 11, 12, 13 and 14 show plots of the separatrix at the electrostatic septum for both $1/2$ and $1/3$ integer resonant extraction for zero and $.04\pi$ stable phase space. These plots are not in normalized phase space so that the phase angle does not appear to be 35° . From these computer calculations we can extract data on extraction losses, orbit maxima, and step size across the septum (the extraction aperture). Figures 15 and 16 give plots of extraction inefficiency, orbit maxima, and step size versus the septum radial offset for $1/3$ integer extraction for the finite and zero stable phase space cases. In these plots one can see the extraction inefficiency (or beam loss) falling as the septum radial offset increases. As the extraction losses decrease the step size and orbit maxima (XMAX in the plots) show a corresponding increase (note the different scales on the right hand axis). An analysis of $1/3$ integer extraction has been made by Don Edwards (see UPC 15), and one of the results obtained shows that the optimal value for the sextupole strength (minimizing extraction losses) is when step size is equal to the septum radial offset. For a 10-mm aperture extraction channel the maximum allowable step size is obviously 10 mm. Figure 15 shows the sextupoles adjusted to this optimal value giving an ~ 10 mm step size for a septum offset of 10 mms and an orbit maxima of ~ 2.0 cms, i.e. the design conditions. The extraction losses are $\sim 1.5\%$ in this case. Figure 16 gives the results for the zero stable phase space. [Figure 17 shows the analytic predictions for the results in Fig. 16 obtained

from the theoretical approach described in UPC 15. The agreement between the two is good to $\sim 5\%$, consistent with the first order approximations used in the theoretical model.] For a 10 mm septum offset the step size has now increased to 14 mm and the orbit maximum to 2.6 cms. This effect of the increasing step size with decreasing stable phase space area is common to all extraction systems and is due to the fixed points, from where extracted beam starts to grow, moving away from the septum allowing the beam to generate a larger step size before reaching the septum. In order to bring the orbit maximum and step size back within the defined tolerances the septum offset must be reduced to ~ 9 mm, looking back to Fig. 15 for a 9 mm septum offset the extraction losses are now $\sim 2\%$ with a 6 mm step size. Hence we have arrived at a situation where during the extraction cycle the extracted beam size changes by almost a factor of 2 with very high extraction losses. The underlying reason for this behavior is of course the imposition of the 2.0 cm aperture criterion which forces us to employ relatively strong extraction elements to generate a sufficient step size at a small septum offset which is consequently going to give a step size which is a strong function of position. The large extraction losses are also due to the 2.0 cm effective aperture which requires the septum radial offset to be small. The 2% extraction loss figure is calculated assuming a 0.003" electrostatic septum thickness. In order to achieve a septum kick of sufficient strength (~ 70 μ rad) at 1000 GeV using electrostatic fields similar to those currently in use, some 25 - 30' of septum is necessary. It is doubtful whether a septum of this length can be aligned to within 0.003" and a figure $\sim 50\%$, higher than this value is more realistic implying extraction losses of $\sim 3\%$, an unacceptably high figure. The 1/2 integer extraction shows essentially the same behavior as the 1/3 integer extraction.

So, to summarize the initial results obtained on the Tevatron extraction, we can say that the ± 2.0 cm aperture criterion severely constrains any extraction system to high losses (up to 3%) and extracted beam instabilities.

The next question to be answered is whether this is the best we can do without attempting a major redesign of the dipole aperture. Let us consider the equation relating orbit maxima to step size and septum offset. As derived in the UPC 15 we have

$$x_{\max} = \frac{(x_s + \Delta)}{\cos \theta} \left(\frac{\beta_{\max}}{\beta_s} \right)^{1/2}$$

where θ = the phase angle of the separatrix at the septum

x_s = septum offset

Δ = step size

β_{\max} = maximum horizontal beta in a standard cell

β_s = beta at the septum.

It is immediately apparent that an increase in the value of beta at the septum would decrease the orbit maximum if all other values were kept constant, which means that from an extraction point of view we have increased the effective aperture of the machine. Figure 18 outlines a scheme devised by Tom Collins to modify the machine lattice around a long straight section to increase the horizontal beta value while leaving the lattice in the rest of the ring unchanged. The major effects of this high beta insertion are severalfold; the maximum horizontal beta value (225 ms) is now at the upstream end of the long straight section which is where we would like to place the extraction septa to minimize the effect of extraction losses causing magnet quenches. The threefold increase in beta increases the effective septum kick by a similar amount, allowing a 10'-12' electrostatic septum to generate sufficient spatial separation. Alignment of a septum of this length to within 0.003" is possible using existing fabrication techniques.

Increasing beta from 70 ms to 225 ms is equivalent to increasing the effective machine aperture by a factor of 1.8 for the extraction system.

Figures 19 to 22 show the results obtained using this high beta insertion for both 1/3 and 1/2 integer extraction. Using the same 2.0 cm aperture limitation as before we find that the extraction losses have now been reduced to $\sim 1\%$. The size of the extracted beam throughout the extraction cycle is now constant to within 20%. Figure 23 gives the analytic predictions for the results shown in Fig. 22, the agreement is again good to within 5%. One more fact which has emerged from this analysis is that substantial reductions in the strength of the extraction elements can be made for rather small changes in aperture (or extraction inefficiency). For example in the 1/2 integer case, a 33% reduction in octupole field strength would cause a relatively small increase (0.3%) in extraction losses. A phase space plot showing the effect of an electrostatic septum producing a 30 μrad kick on the 1/2 integer extraction separatrix is given in Fig. 24. Figure 25 shows the same separatrix at the magnetic septum in the next straight section, with a spatial separation of ~ 6 mms between the circulating and extracted beam.

In conclusion then we can say that the high beta insertion has reduced the extraction losses to a very tolerable level, created the possibility of placing the extraction septa at the upstream end of the long straight section, and has stabilized the beam spot size during extraction.

MAGNET 115 (DELTA BDL)/BDL
4000 AMPS 1.0*10-4/DIU

-9-

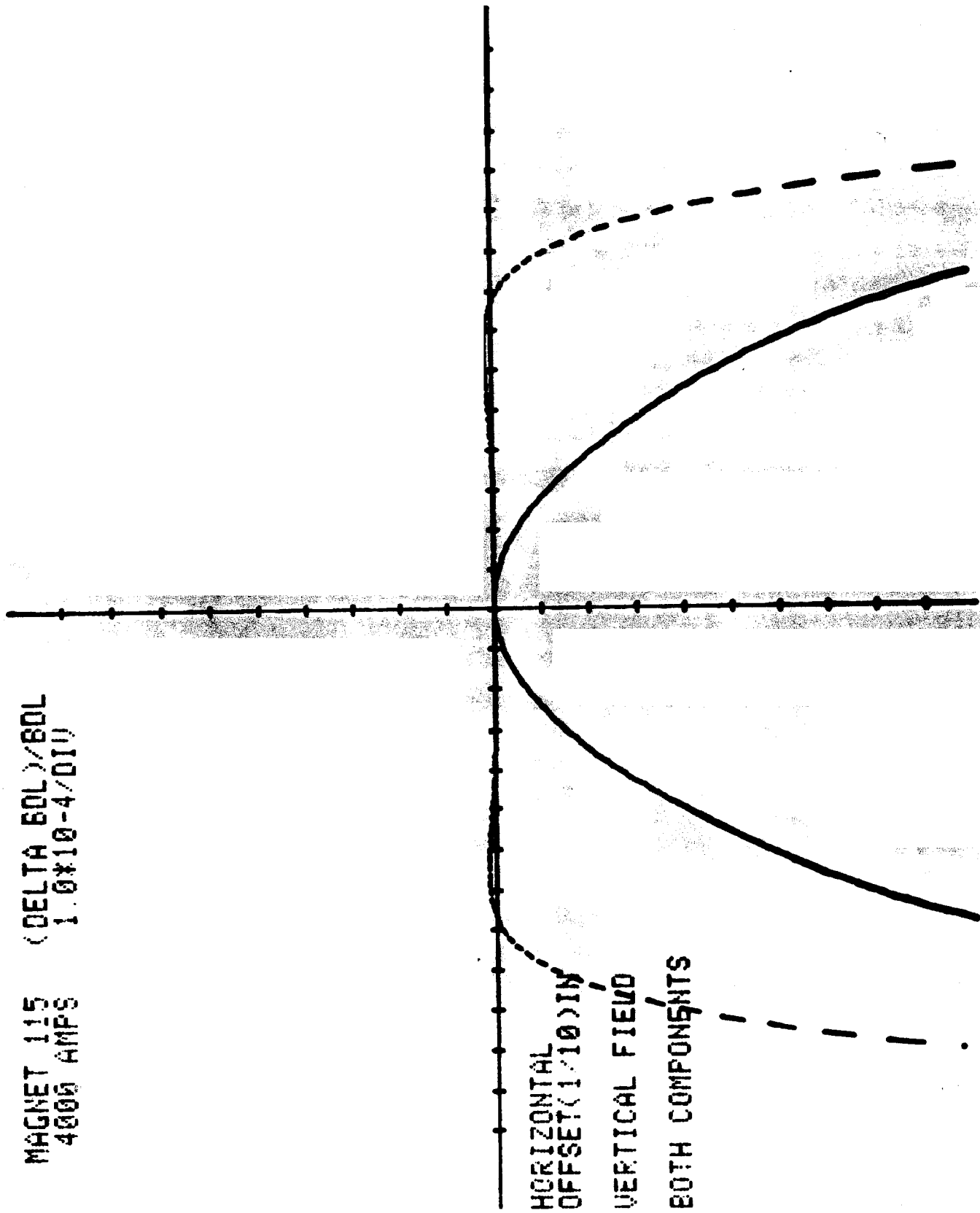


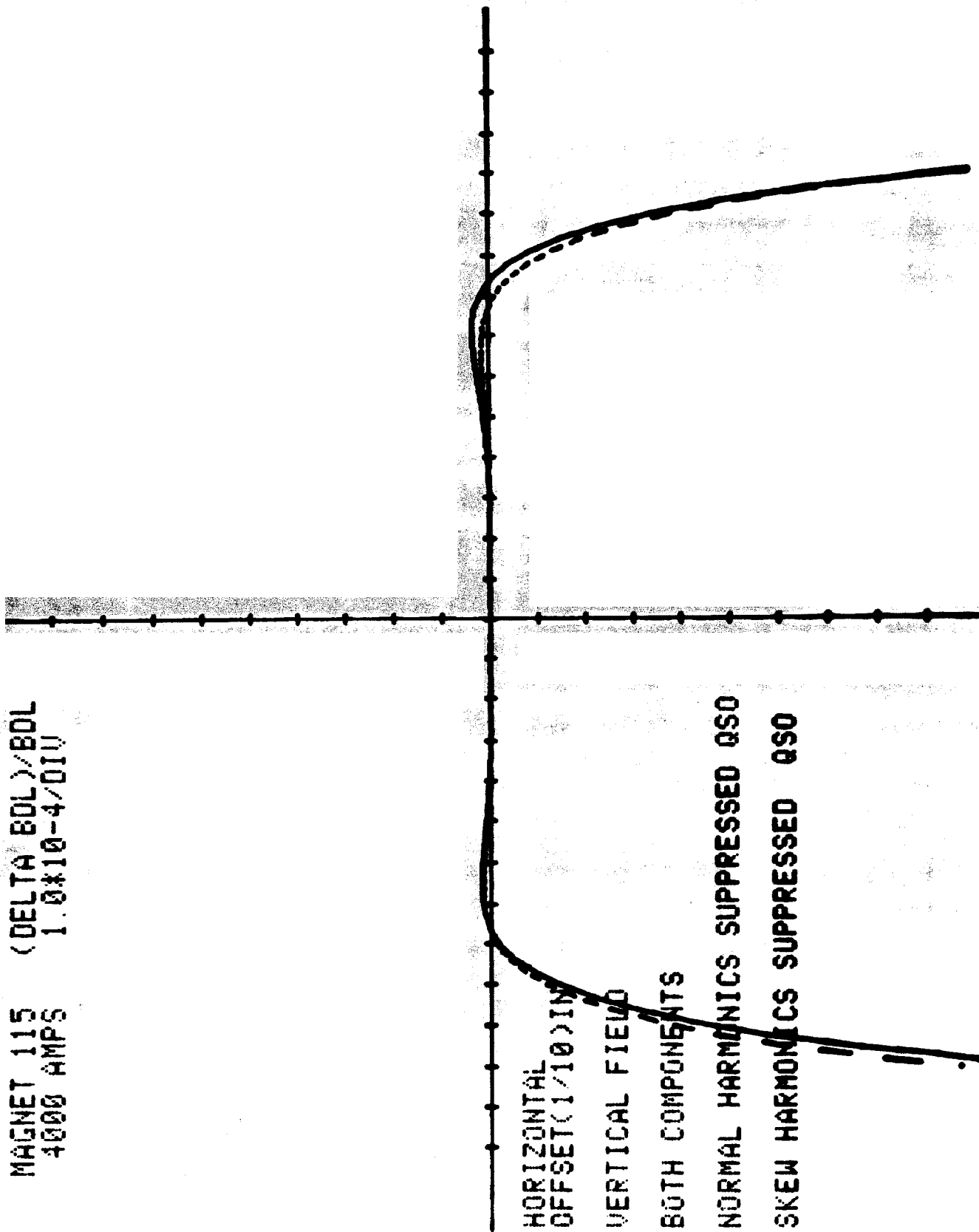
Fig. 1

MAGNET 115 (DELTA BOL)/BOL
4000 AMPS 1.0x10-4/DIV

-10-

HORIZONTAL
OFFSET(1/10)IN
VERTICAL FIELD
BOTH COMPONENTS
NORMAL HARMONICS SUPPRESSED QSO
SKEW HARMONICS SUPPRESSED QSO

Fig. 2



28-NOV-78 10:52

0.50 CMS PER DIV
HORIZONTAL PHASE SPACE
TUNE 19.45000
BETA 67.7165
ALPHA -0.65040

BETA-THETA(MMS)
(NORMALIZED)

POSITION(MMS)

-11-

Fig. 3. 1/2 Integer Extraction
Perfect Dipoles

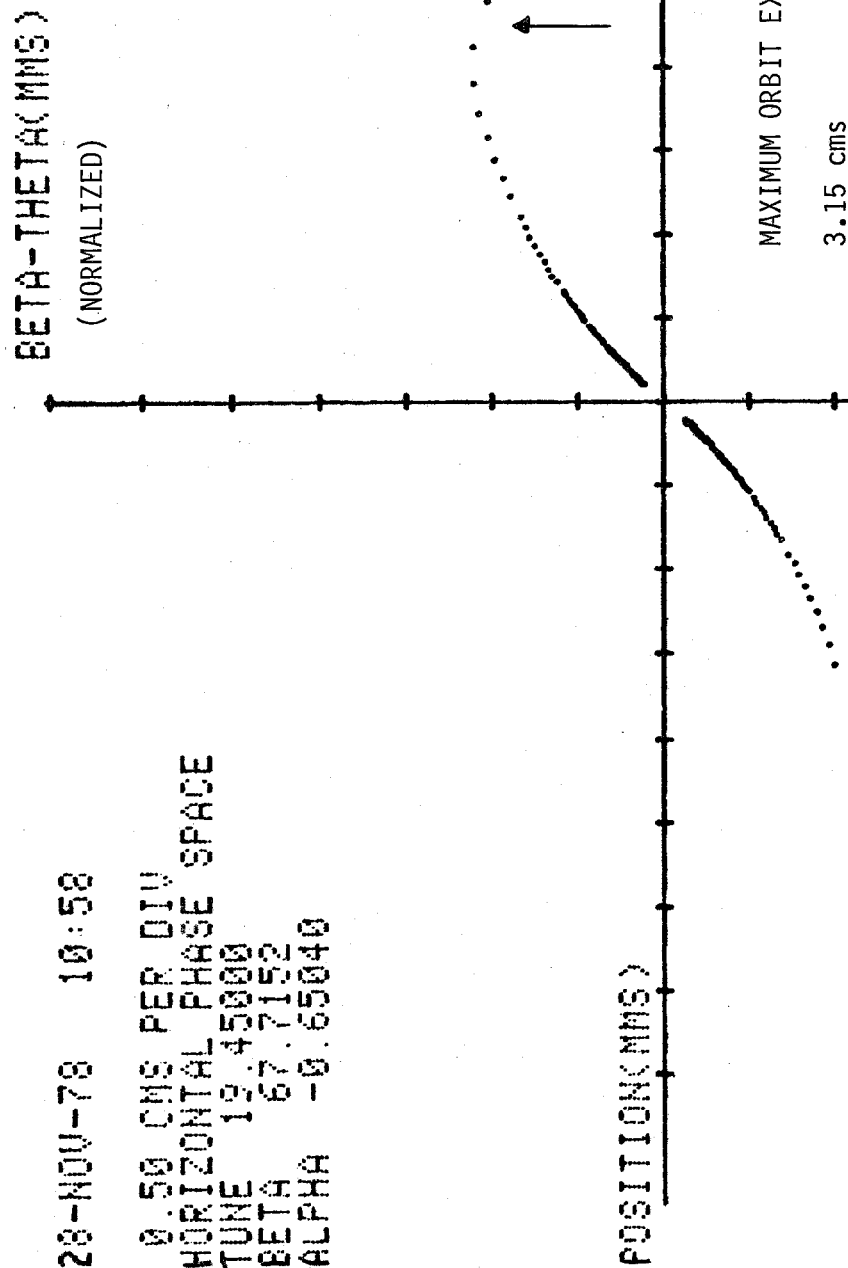


Fig. 4. 1/2 Integer Extraction
 Design Fields

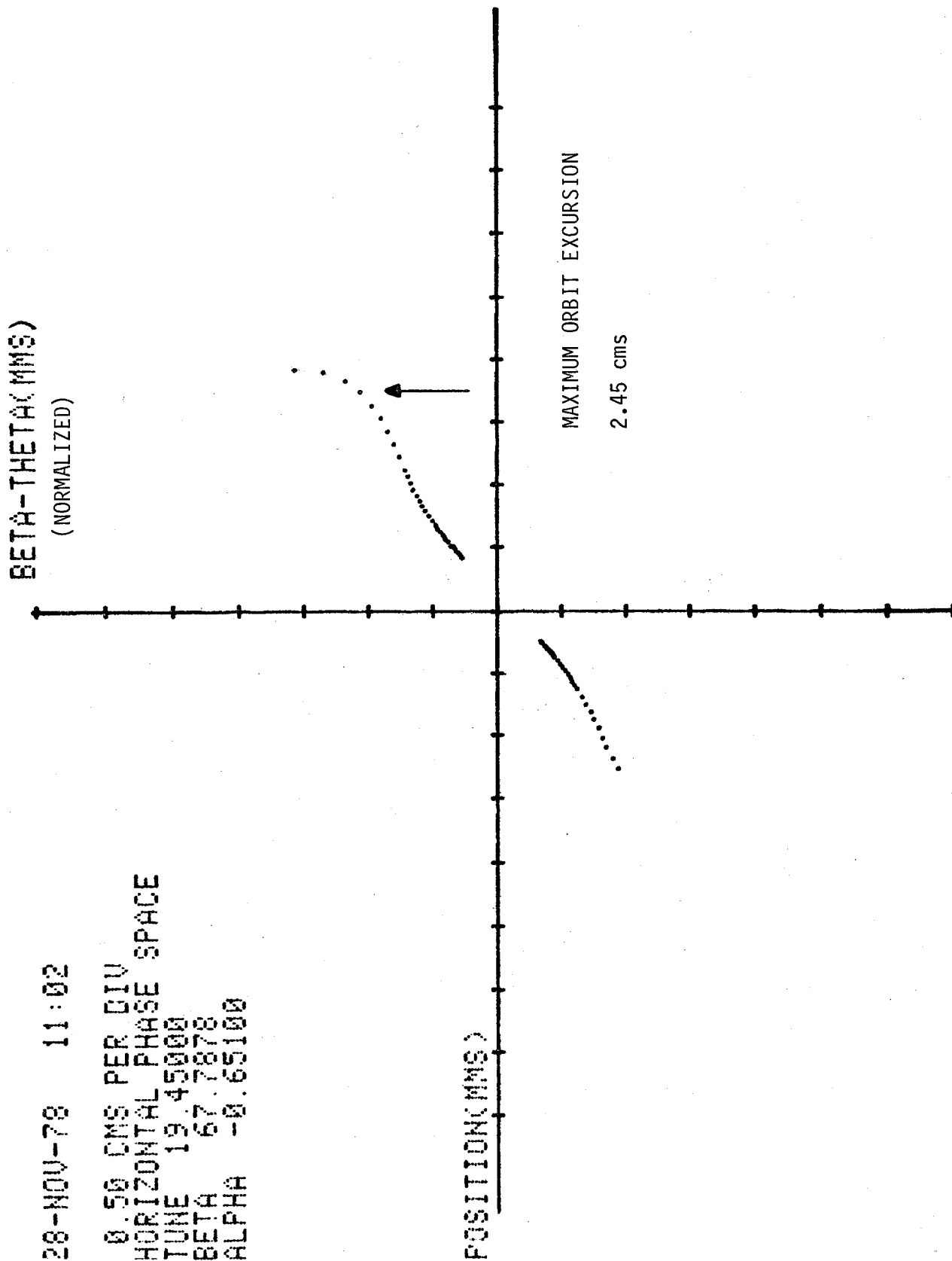


Fig. 5. 1/2 Integer Extraction
 Design Fields
 $\frac{\Delta p}{p} = 0.05\%$

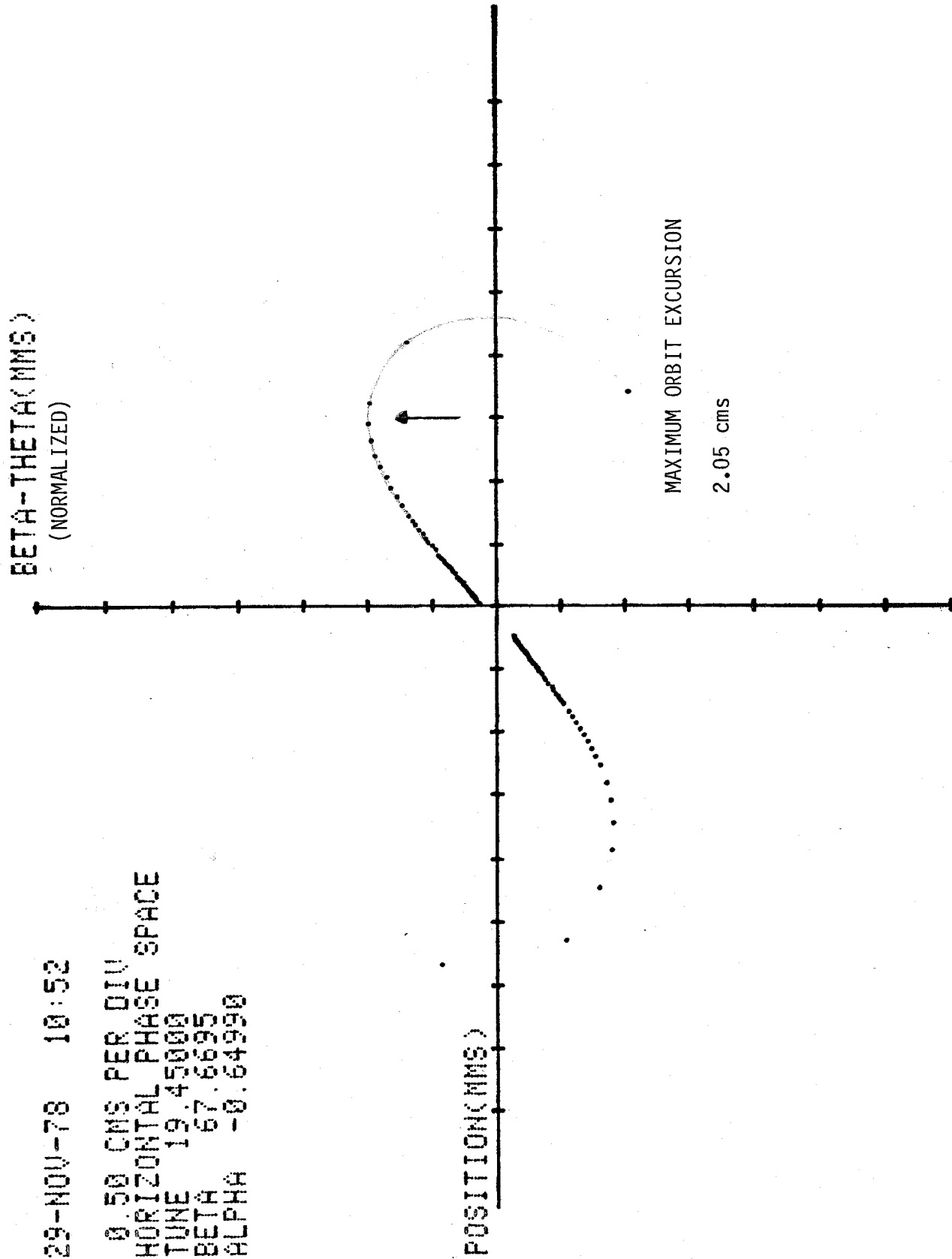


Fig. 6. 1/2 Integer Extraction
 Design Fields
 $\frac{\Delta p}{p} = -0.05\%$

MAGNET 115 (DELTA BOL)/BOL
4000 AMPS 1.0*10-4/OIU

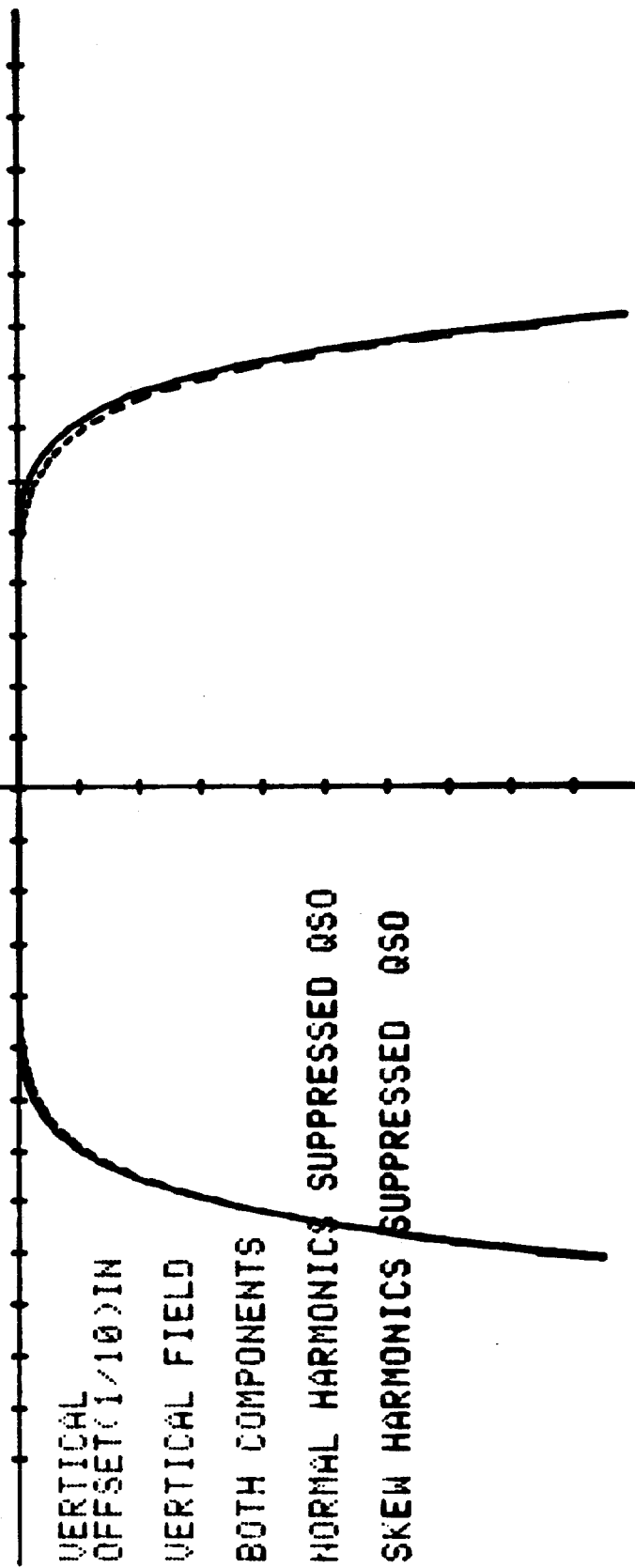


Fig. 7

MAGNET 120 (DELTA BDL)/BDL
3001.6AMPS 1.0*10-4/DIU

VERTICAL
OFFSET(1/10)IN

HORIZONTAL FIELD

BOTH COMPONENTS

OCTOPOLE AND LOWER TERMS SUPPRESSED

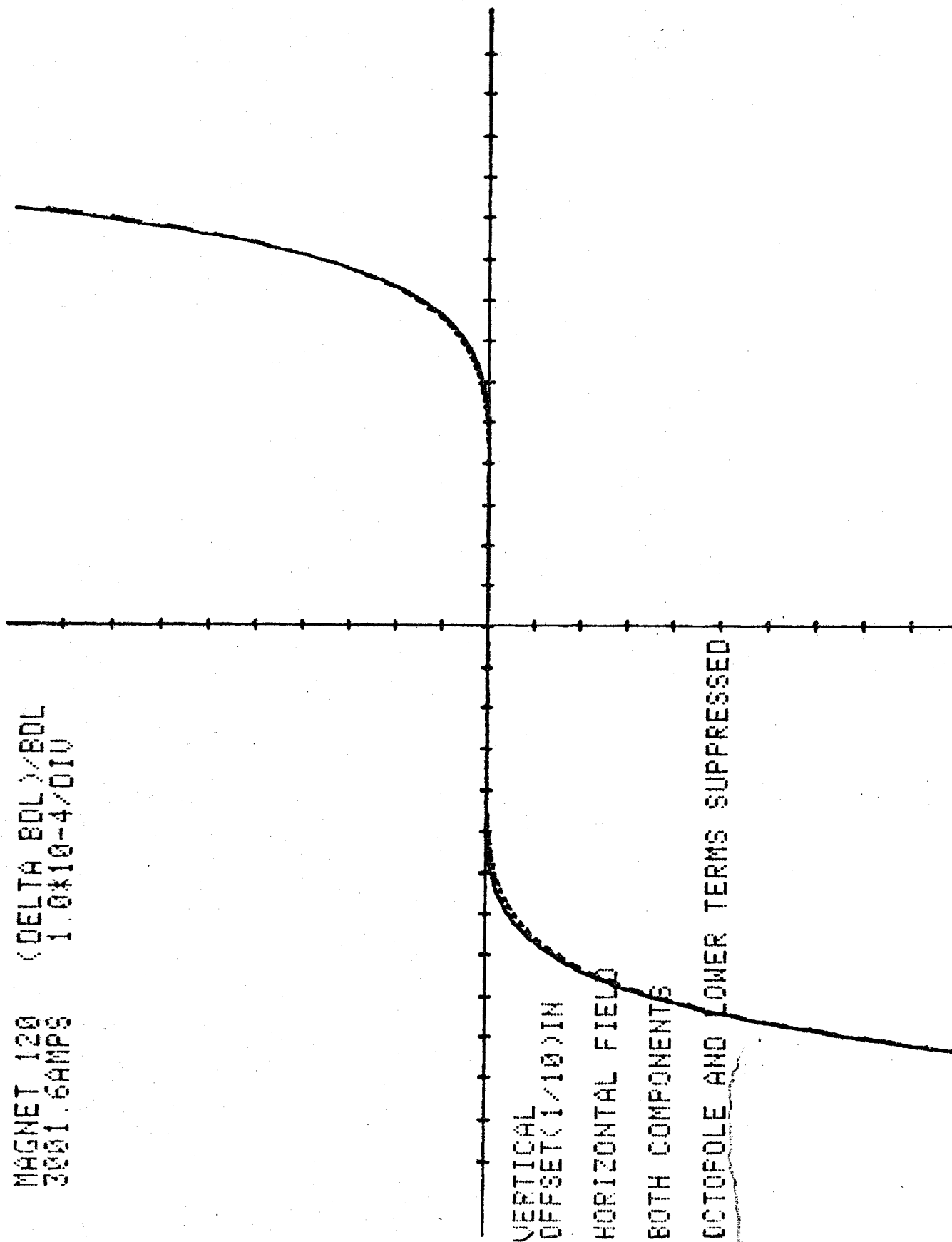
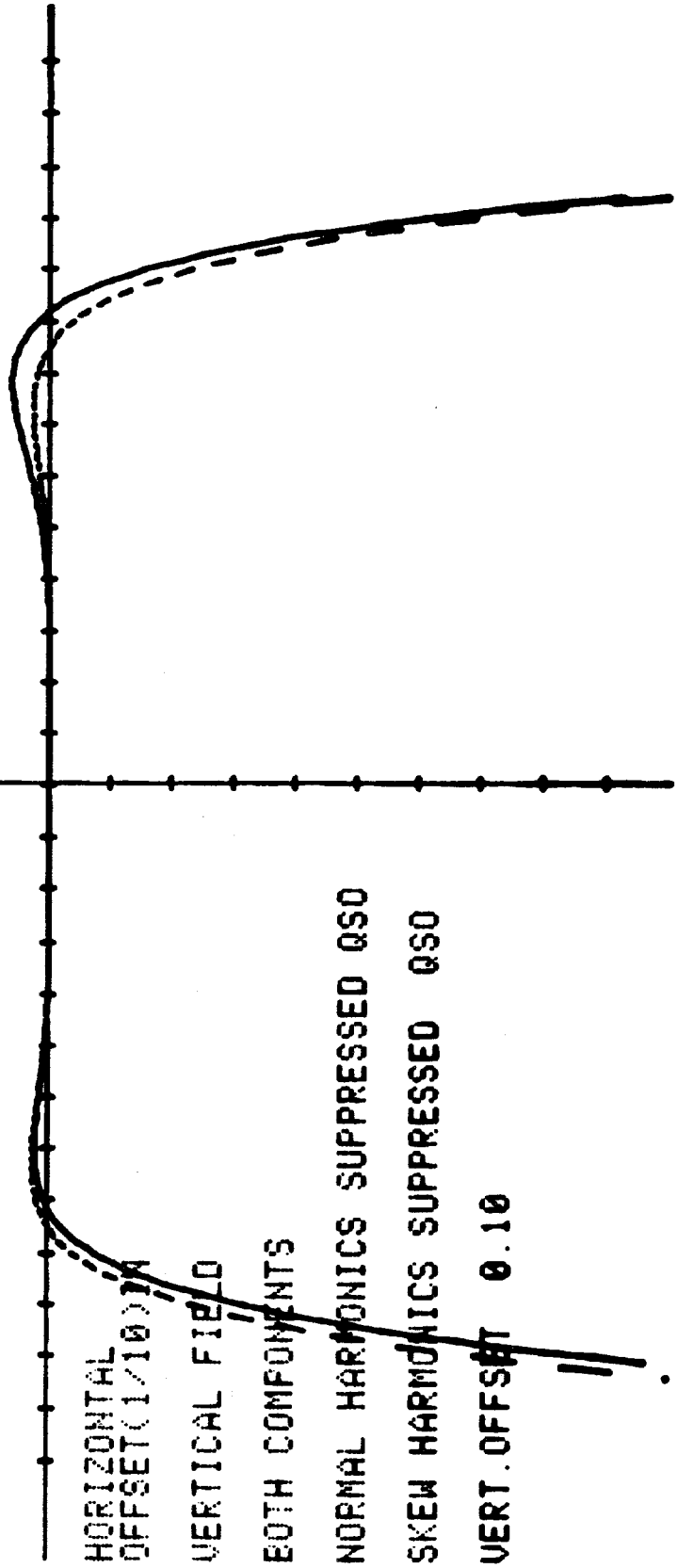


Fig. 8

MAGNET 115 (DELTA BOL)/80L
4000 AMPS 1.0*10-4/DIV



MAGNET 115 (DELTA BOL)/BOL
4000 AMPS 1.0x10-4/DIV

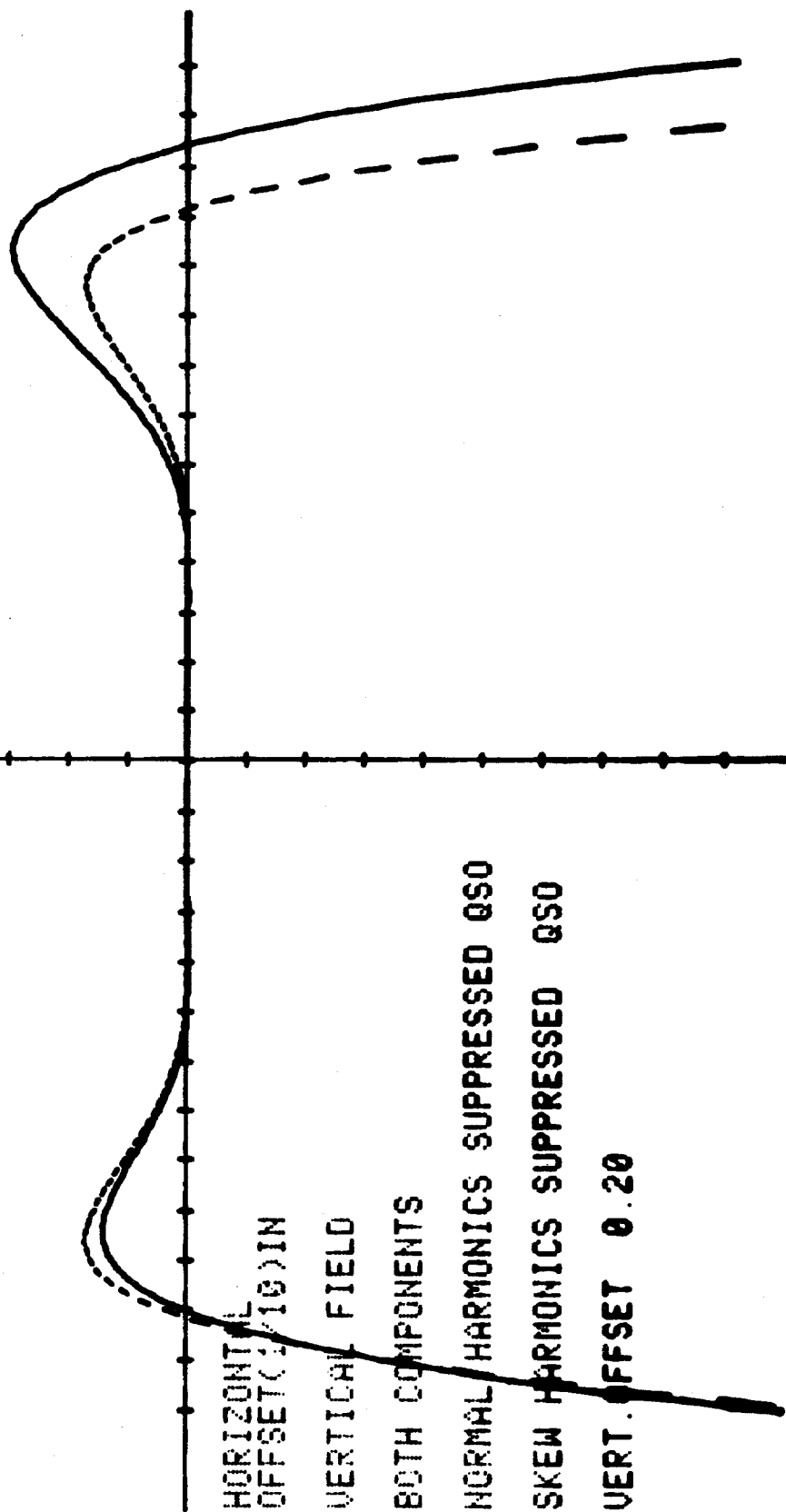


Fig. 10

BETA-THETA(MMS)

30-OCT-78 13:35

0.52 CMPS PER DIV
 TOTAL PHASE SPACE
 TUNE 13.4999
 BETA 8.4955
 ALPHA -0.64220

POSITION(MMS)

0001	B	214.47	0.00	107
0001	D	214.47	0.00	107
0001	F	214.47	0.00	107
0002	A	214.47	0.00	107
0002	C	214.47	0.00	107
0002	E	214.47	0.00	107
0003	B	215.00	3.00	000
0003	D	215.00	3.00	000
0003	F	215.00	3.00	000
0003	A	215.00	3.00	000
0003	C	215.00	3.00	000
0003	E	215.00	3.00	000
SURV		1.05		
SURV		1023.00		

1/2 INTEGER RESONANT EXTRACTION
 .04 π mm mrad STABLE PHASE SPACE

XINIT	0.354
XPINIT	.1093
YINIT	0.000
YPINIT	.0000

Fig. 11

SECRET

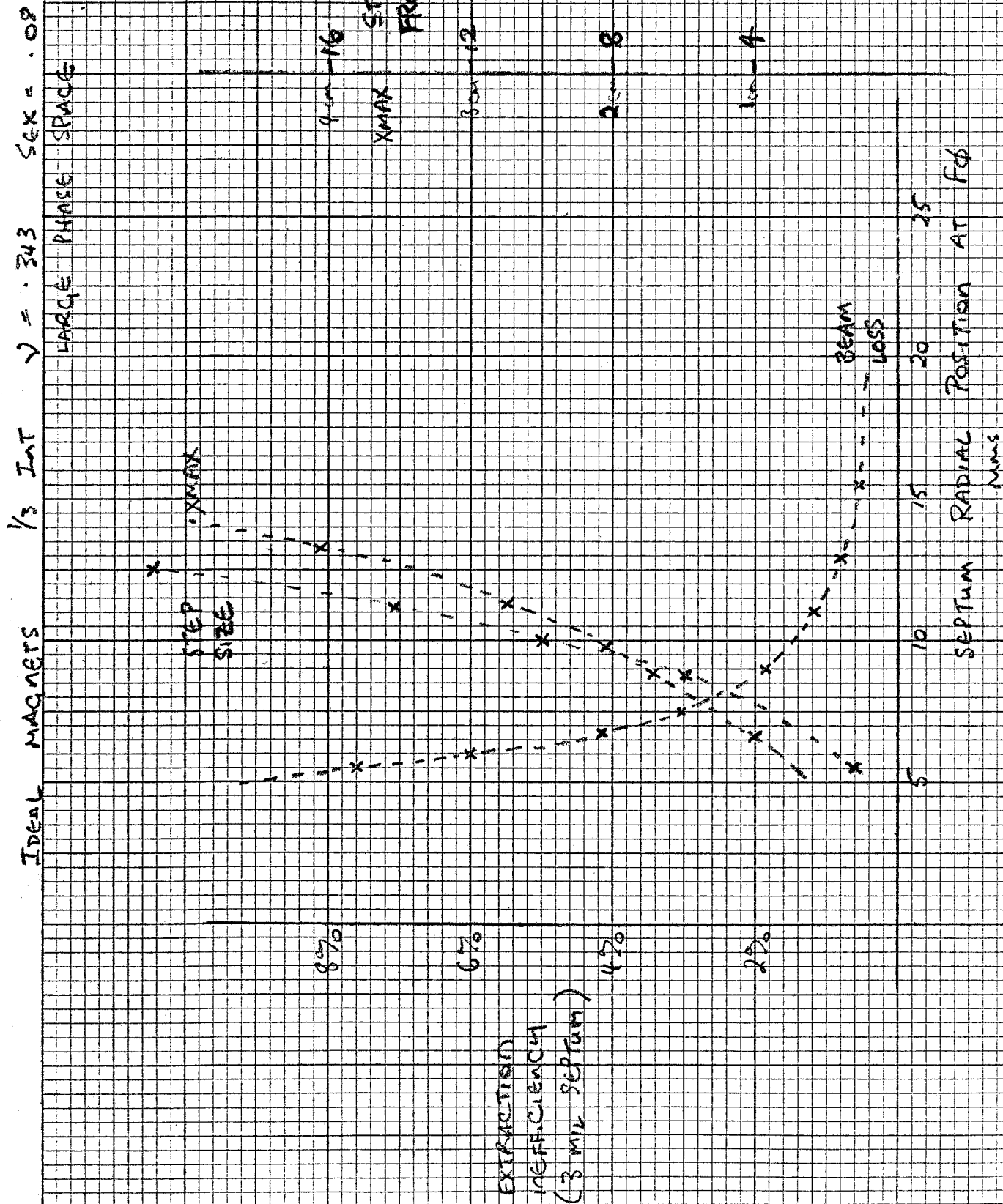


Fig. 15

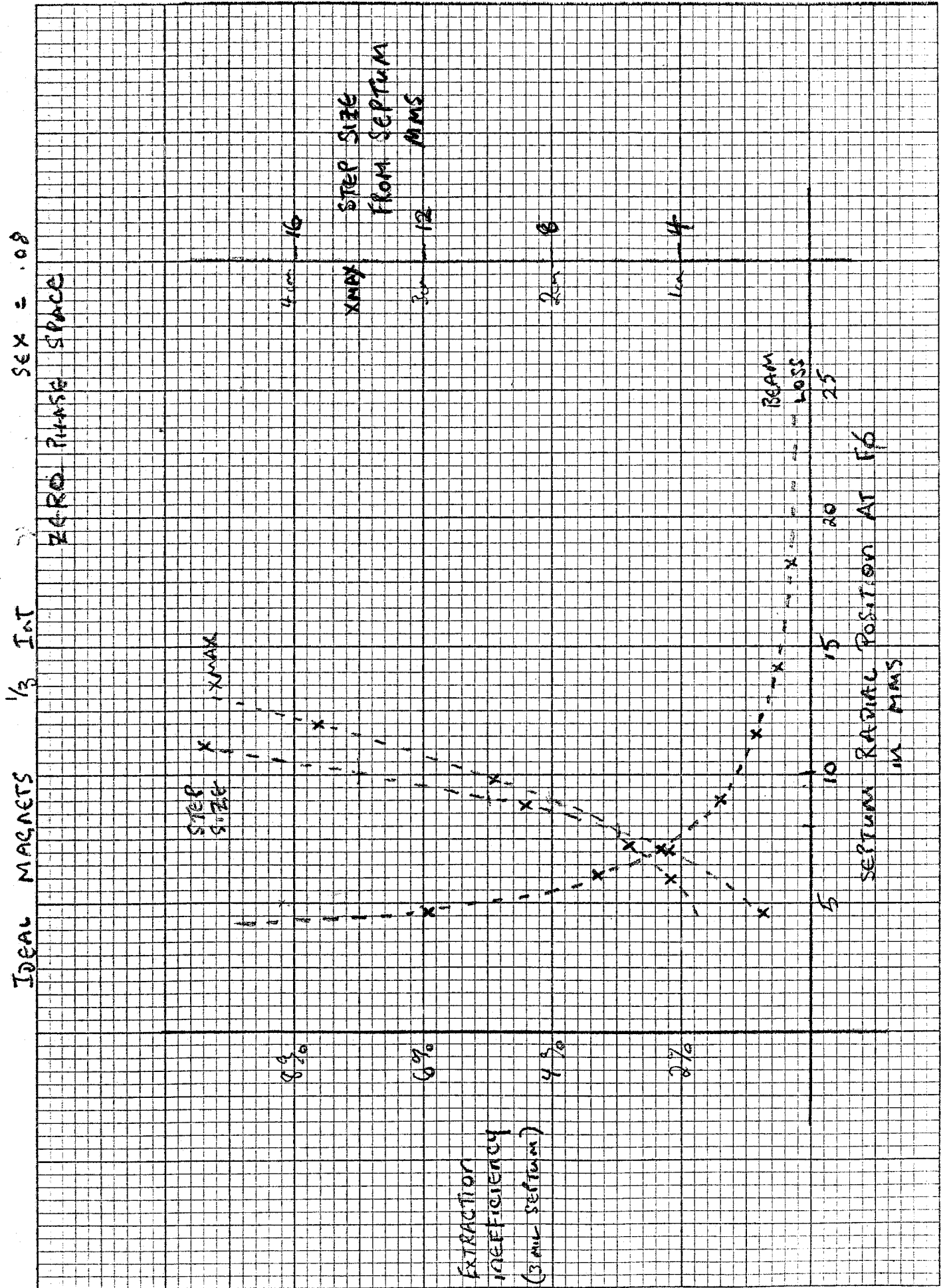


Fig. 16

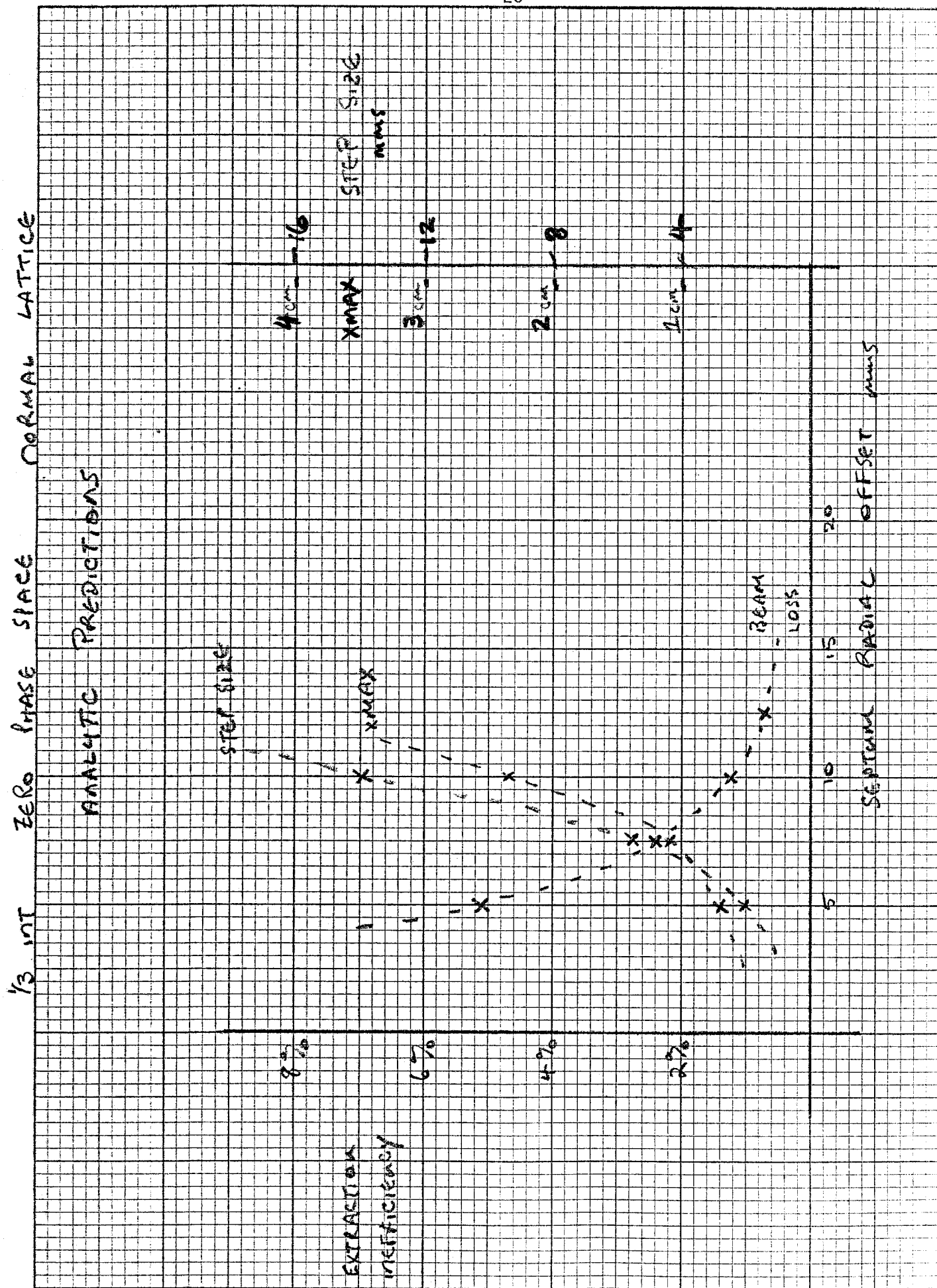


Fig. 17

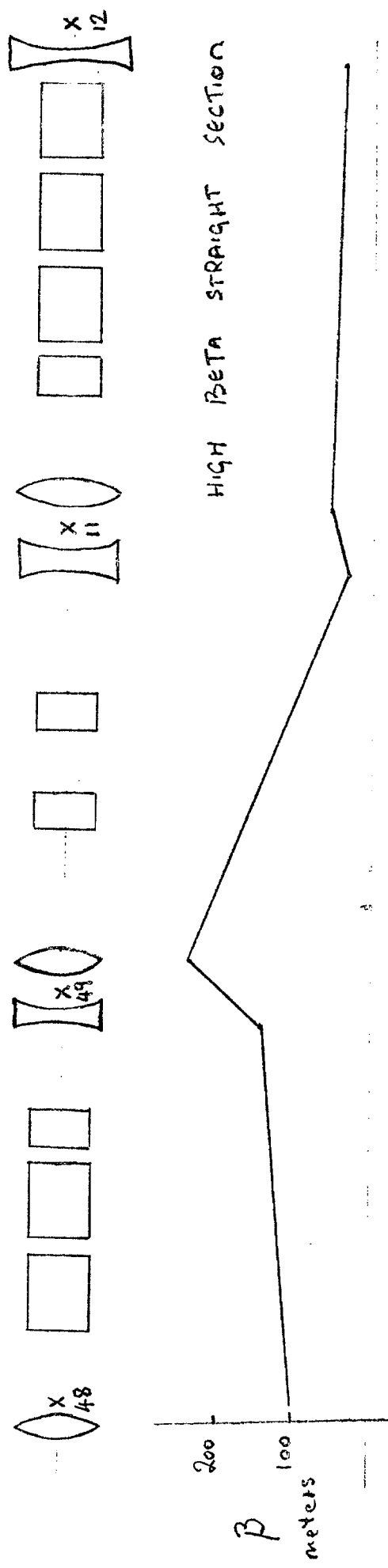
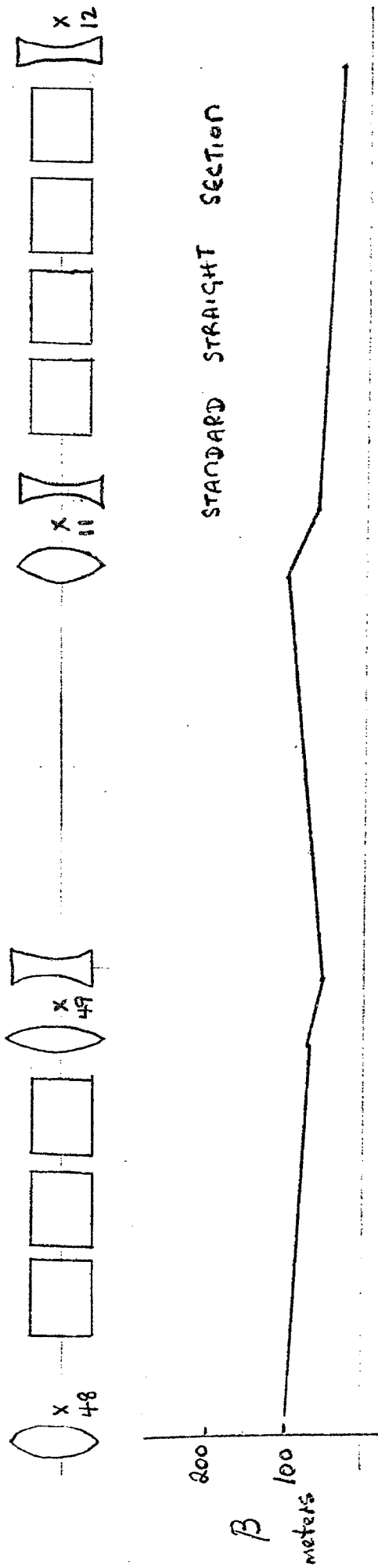


Fig. 18

NOT TO SCALE

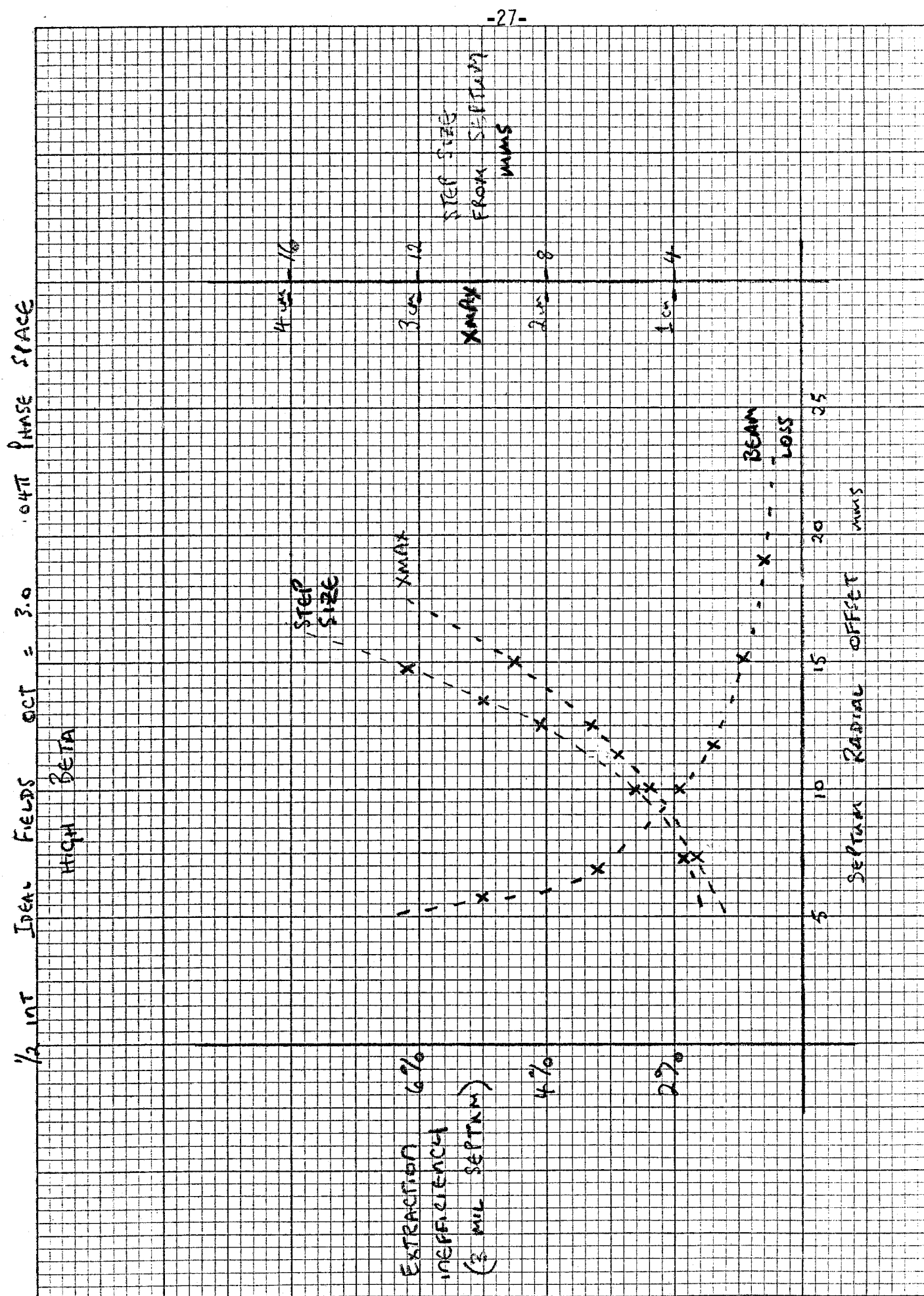


Fig. 19

1/2 INT IDEAL FIELDS OCT = 3.0 ZERO PHASE SPACE

HIGH BETA

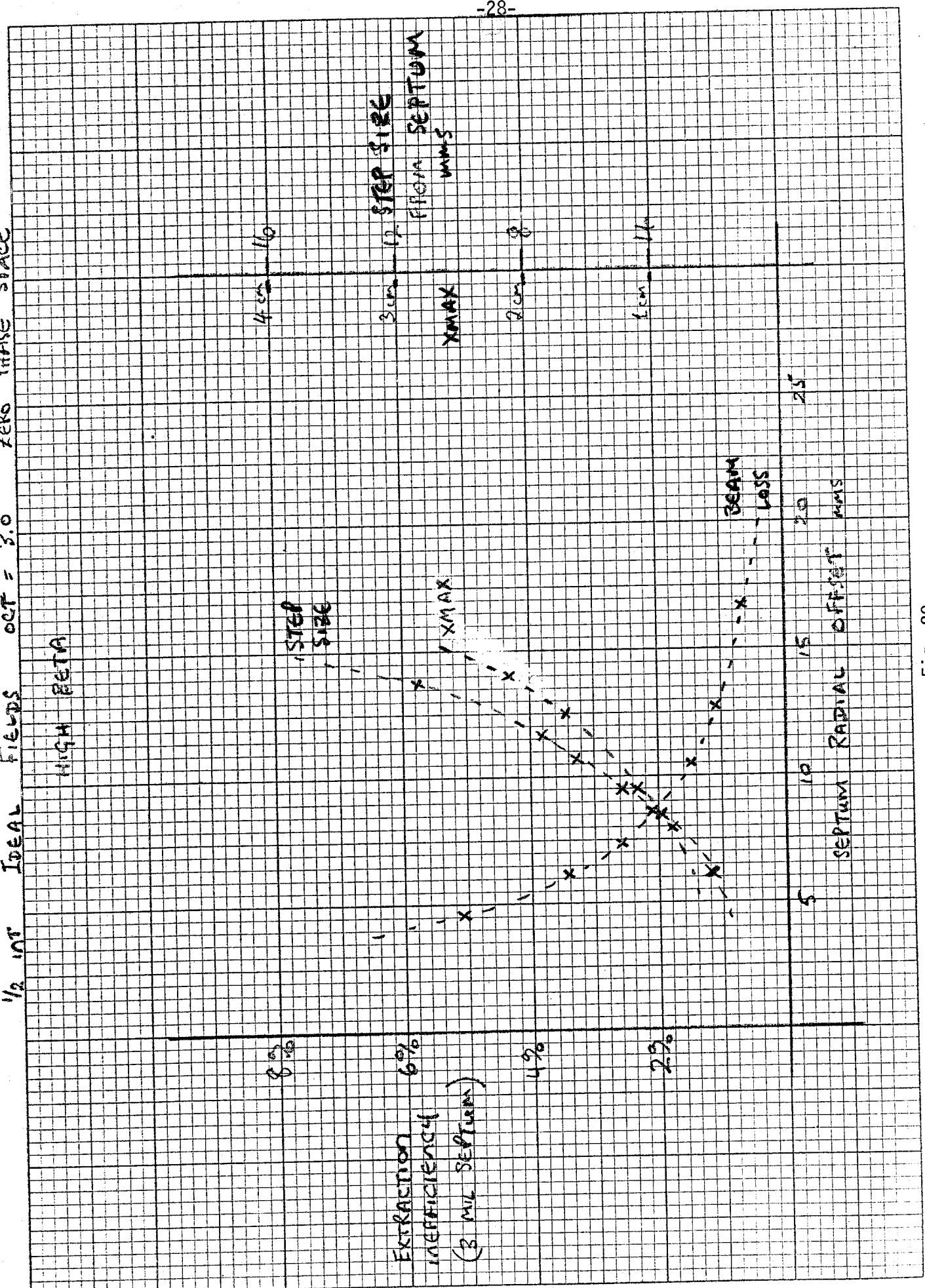


Fig. 20

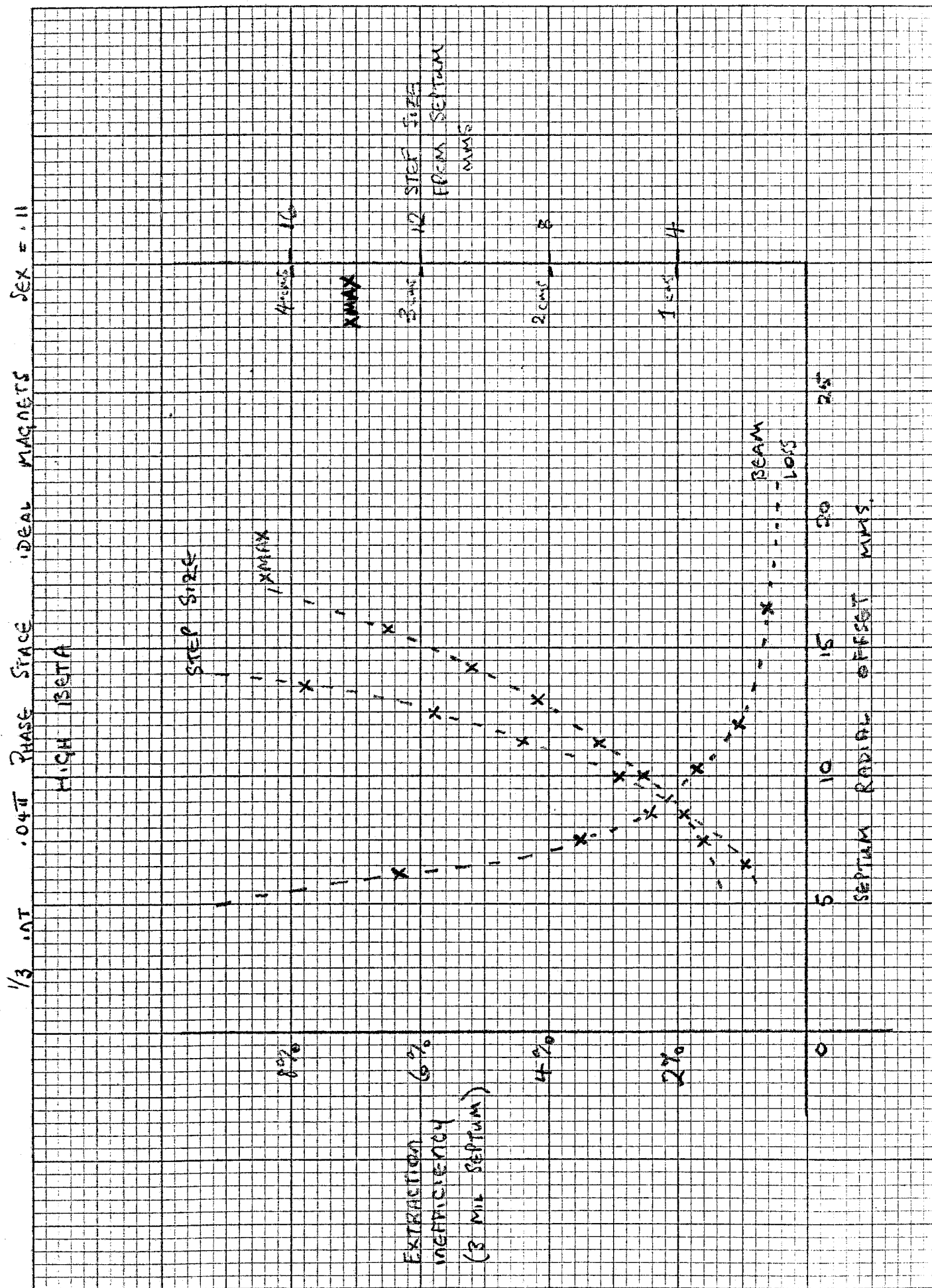


Fig. 21

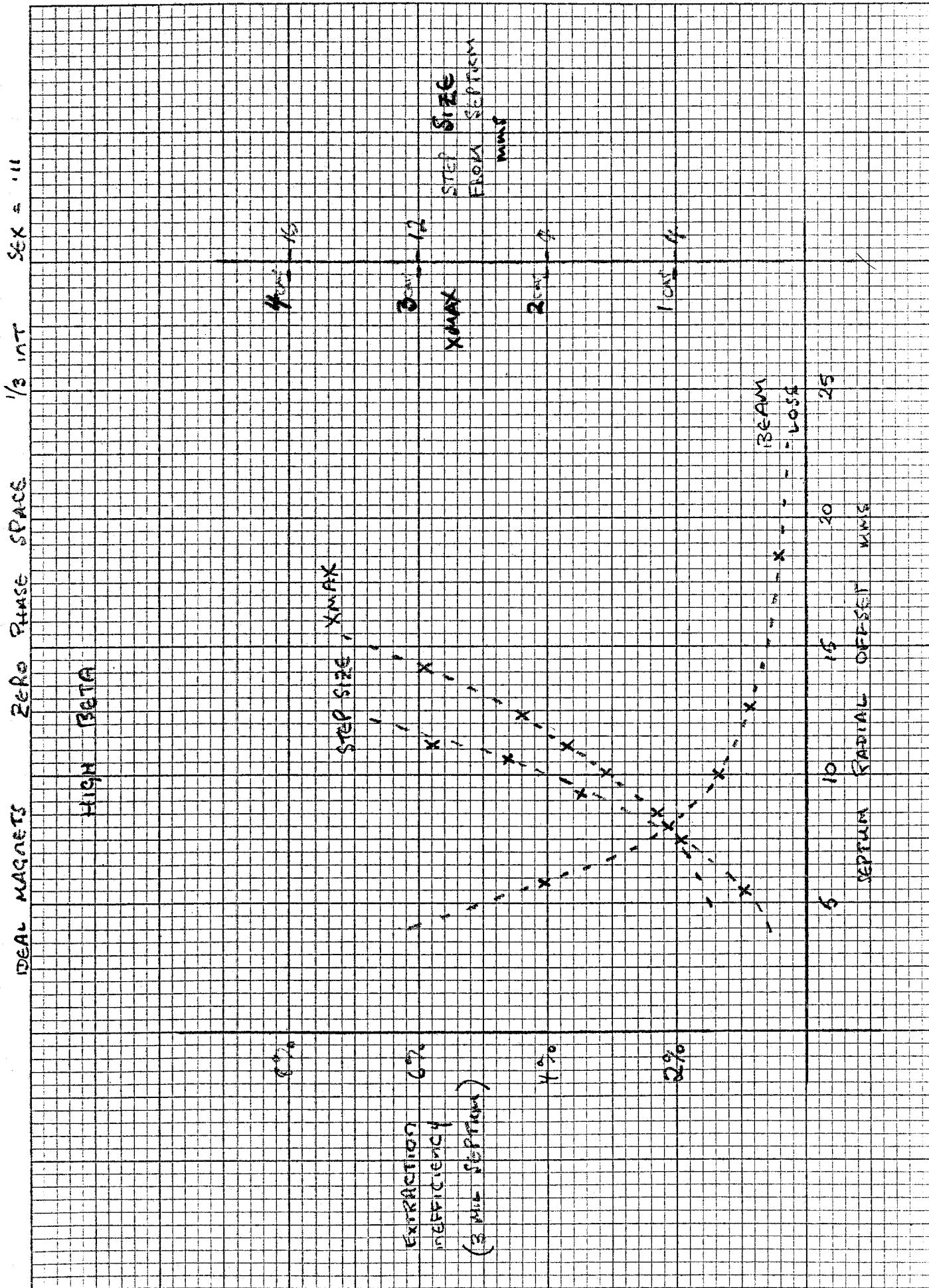


Fig. 22

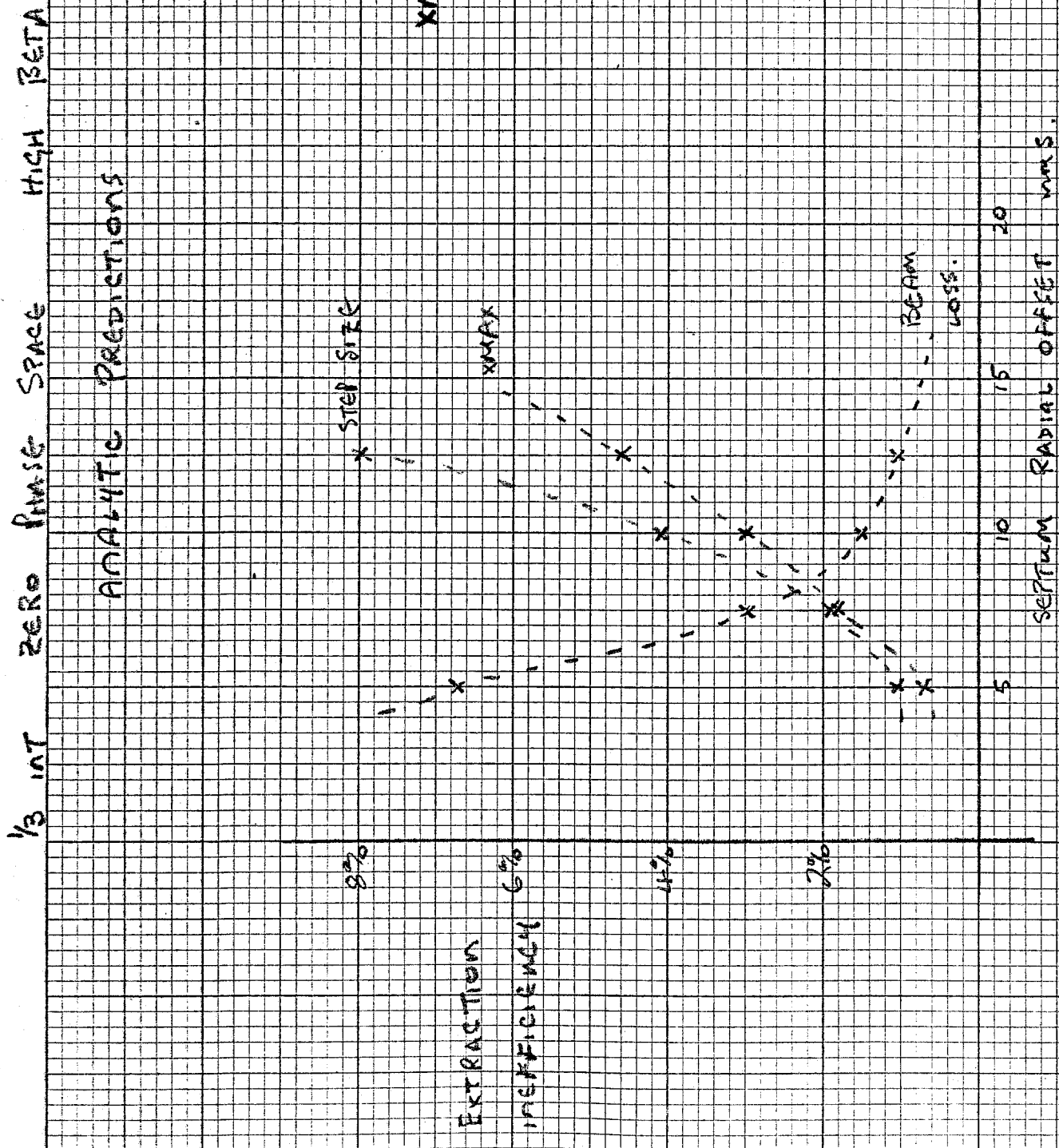


Fig. 23

BETA-THETA(MMS)
BEAM AT SEPTA

29-NOV-79 15:07

0.50 CMS PER DIV
HORIZONTAL PHASE SPACE
TUNE 19.45000
BETA 226.2635
ALPHA 3.82990

POSITION(MMS)

QUD1 B	807.20	0.00116
QUD1 D	807.20	0.00116
QUD1 F	807.20	0.00116
QUD2 A	807.20	0.00116
QUD2 C	807.20	0.00116
QUD2 E	807.20	0.00116
OCT1 B	807.30	3.00000
OCT1 D	807.30	3.00000
OCT1 F	807.30	3.00000
OCT2 A	807.30	3.00000
OCT2 C	807.30	3.00000
OCT2 E	807.30	3.00000

NORMALISED PHASE SPACE

Fig. 24

BETA-THETA(MMS)

BEAM AT LAMBERTSON

29-NOV-78 15:29

0.50 CMS PER DIV
HORIZONTAL PHASE SPACE
TUNE 13.45000
BETA 203.7732
ALPHA 2.85860

POSITION(MMS)

QU01 B	807.20	0.00116
QU01 D	807.20	0.00116
QU01 F	807.20	0.00116
QU02 A	807.20	0.00116
QU02 C	807.20	0.00116
QU02 E	807.20	0.00116
OCT1 B	807.30	3.00000
OCT1 D	807.30	3.00000
OCT1 F	807.30	3.00000
OCT2 A	807.30	3.00000
OCT2 C	807.30	3.00000
OCT2 E	807.30	3.00000

NORMALISED PHASE SPACE

Fig. 25

